An Evaluation of RSP Cloud Top Height Observations During the SEAC⁴RS Campaign

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Background

Cloud top height (CTH) affects the radiative properties of clouds (IPCC, 2013). Models have indicated cloud heights increase in a warming climate which results in a globally averaged forcing of +0.35 (+0.09 to +0.58) W m^{-2} °C^{-1} (IPCC, 2013).

Improved CTH observations will allow for improved sub-grid parameterizations in large-scale models. Accurate information on CTH is also important when studying variations in freezing point and cloud microphysics. More accurate observations of cloud top height will lead to a better understanding of its relationship to cloud thermodynamic phase, atmospheric dynamics and relative humidity. In turn, accurately determining CTH is important when studying variations in freezing point and cloud microphysics (van Diedenhoven et al., 2012, 2014).

NASA's Research Scanning Polarimeter (RSP) is able to measure cloud top height using a novel multi-angular contrast approach that is a variation on the method described in by Marchand et al. (2007). The RSP (Cairns et al., 1999) is an airborne prototype of the Aerosol Polarimetry Sensor (APS) that was on-board the lost Glory satellite. RSP has 9 bands in the visible/near infrared and shortwave infrared and it makes polarimetric and total intensity measurements at 152 evenly spaced viewing angles over a range of 120°. RSP scans along the aircraft track and the data from the actual RSP scans can be aggregated into "virtual" scans consisting of the reflectance at the full range of viewing angles at a single footprint on the cloud top (Alexandrov et al., 2012).

During SEAC4RS, the RSP was mounted on the ER-2 aircraft along with other instruments that made simultaneous measurements of CTH including the Cloud Physics Lidar (CPL).

Research Objective

The primary objective of this work is to: present an overview of the RSP cloud layer height retrieval technique; use specific cases to demonstrate the RSP's different abilities of retrieving single and multi-layered cloud heights; compare the results with the CPL; and conduct an analysis on 4 days of observed data. A discussion of the resulting abilities and limitations of the technique concludes the presentation.

Cloud layer heights are calculated using 3 band configurations: the 670 nm; the 1880 nm; and a combined 670/1880 nm joint configuration. Differences in the cloud layer heights, and their ability to identify multiple cloud layers is explored. The scan-by-scan analysis demonstrates the workings of the approach on its smallest scale and illustrates ideal and challenging retrievals which, when compared with CPL, the accuracy of the approach can be calculated. An analysis on 4 days of data calculates the results and accuracy of the different approaches on over 65,000 retrievals allowing for direct comparison and also allows for improvements to be made to filtering coefficients, which are used to identify single and multilayered cloud scenes.

Measurements

Fig. 1. NASA ER-2 Aircraft

- NASA-led field campaigns have collected a multitude of remote sensing information with the goals of enhancing our understanding of cloud properties, cloud processes and to improve our ability to observe clouds with current and future satellite missions. The SEAC4RS campaign collected information with a variety of instruments including polarimeters, spectrometers, lidar, radar as well as in situ measurements. The RSP and the Cloud Physics Lidar (CPL) were onboard the ER-2 aircraft.
- Data used in this analysis was collected over 4 days during the NASA SEAC4RS experiment on September 2nd, 4th, 16th and 20th 2013. Special focus on a leg of the ER-2 aircraft flight path on September 16th 2013 at 16.9 U.T. when it encountered a multilayered cloud. During this period, the Research Scanning Polarimeter (RSP) and Cloud Physics Lidar instruments made simultaneous measurements.

Method

A single RSP scan makes 150 nearly simultaneous measurements sweeping ±60° from nadir in 0.8° increments along the aircrafts track. When the aircraft is flying straight, multiple scans will measure the same feature multiple times from a variety of angles.

For this study, the intensity measurement at nadir for a central scan and ±8 scans reveals how reflectance varies over sequential scans and is used as a footprint. This footprint is used to calculate cumulative cross-correlation values along all viewing angles for aggregated height values ranging from 0 to 20 km using 100 m increments. This process is then repeated for all scans creating a correlation map, figure 2(b,c,d).

$$\rho_{xy} = \frac{1}{n}\sum_{y=0}^{n}\frac{(f_x-\mu_f)(Y_{x,y-a}-\mu_y)}{\sigma_f\sigma_y} \quad \textbf{Eq. 1}$$

The highest correlation value is in most cases taken to be the primary layers height. Additionally, using these varying correlations, it is hypothesized that the RSP can identify separate cloud layers and associated altitudes for up to 3 layers when valid second and third peaks can be identified. To calculate peaks in the correlation maps, a boxcar smoothing function is used; in this case the boxcar function was 9 values wide. Using the smoothed data, a derivative of the data is taken revealing peaks. Second and third peaks are considered valid cloud layers if: the peak is farther than 1.2 km from the previous peak; the peak is higher than 1.5 km and lower than 19.0 km; additionally the peaks correlation value must be higher than 0.15 and also be at least 80% of the magnitude of the primary peak. Up to 3 Gaussian functions are fit to the correlation data keeping the offset and magnitude values constant and finding the least squares fit of the Gaussian width. Shown in equation 2 below, where *a* is the magnitude, *b* is the offset and *c* is the width. The width value is used as an indicator of uncertainty in the cloud layer height.

$$f(x) = a\exp\left(-\frac{(x-b)^2}{2c^2}\right) \quad \textbf{Eq. 2}$$

Results

The method outlined above is used to calculate cloud height values using the RSP's 670 nm band, 1880 nm band and a combination of the two. This data was collected September 16th 2013 between 16.6 and 17.85 U.T. It can be observed in the CPL extinction coefficient plot (figure 3 top) that the scene contains sections of single layered clouds, dual layer and even some 3 layered scenes beginning after 16.9 U.T.

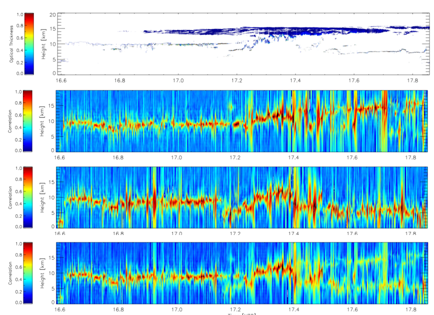

Fig. 2. (a) CPL Extinction coefficient plot (b) RSP 1880 nm band correlation map (c) RSP 670nm band correlation map (d) RSP 1880 & 670 nm band correlation map

Results

It can be seen qualitatively that the 1880 nm correlation map (figure 2b) senses higher layers in the scene, and with regions where multiple peaks are evident (17.2 U.T.)

The 670 nm correlation map (figure 2c) does not have significant scattering from the higher layers but can see the lower layer in the second half of the flight leg quite well. The combined correlation map (figure 2d) sees the higher and lower layers.

Figure 4 a-d show CPL extinction coefficient plots (left) alongside corresponding single scan RSP correlation values. The peaks that were found after the data was smoothed and the derivative was taken, as per the technique described in *Method*, are shown as green points in all. Figure 4a shows an example of a single cloud layer; figure 4b a dual layer case; figure 4c a triple layer example and 4d an example where the CPL sees a higher layers which the RSP does not identify.

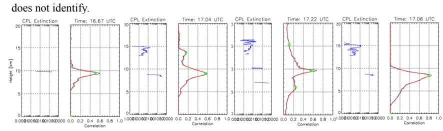

Fig. 3. (a-d) CPL extinction [left] and RSP correlation shown in black with smoothed data shown in red. Identified peaks are shown as green dots.

Filtering the identified peaks results in cloud layers being identified. Figure 6 (top) shows resulting cloud layers for the 1880 nm band, with blue being the largest correlation value, red the 2nd and green as the 3rd. The gray plotted in the background is the CPL cloud layer results. Figure 6 (middle) shows similar results except for the 670 nm band. Figure 6 (bottom) is for the combination (670/1880 nm bands) correlation map.

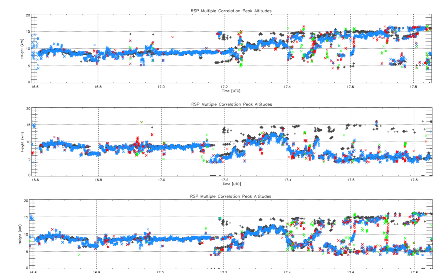

Fig. 4. (top) 1880 nm band cloud layer heights (middle) 670 nm band cloud layer heights (bottom) Combined 1880/670 nm band cloud layer height. Gray points are CPL identified layers, blue is the RSP 1st peak, red the 2nd peak and green the 3rd peak.

The final portion of the analysis uses 4 days of data to quantitatively analyze the skill in the methods ability to sense cloud layers heights in comparison with CPL. The following scatter plots show a direct comparison of the 1st and 2nd peaks compared with CPL. The histogram shows the distribution of the error for the primary peak.

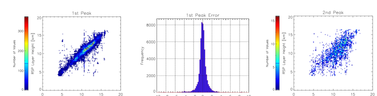

Fig. 5. (left) RSP 1880 nm band and CPL primary peak comparison (middle) distribution of primary peak errors (right) RSP 1880 nm band and CPL secondary peak comparison

Results

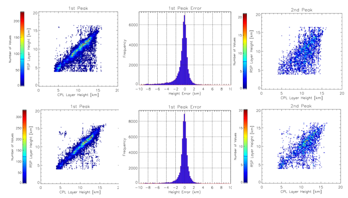

Fig. 6. (top left) RSP 670 nm band and CPL primary peak comparison (top middle) distribution of primary peak errors (top right) RSP 670 nm band and CPL secondary peak comparison (bottom left) RSP combined bands and CPL primary peak comparison (bottom middle) distribution of primary peak errors (bottom right) RSP combined bands and CPL secondary peak comparison

Conclusions

Results for each of the bands show good comparisons with the CPL observed heights. From the table below, the 1880 nm band had the closest comparison to CPL with a large number of data points. The 670 band retrieval had the poorest performance, however, some instances where the CPL was attenuated, possibly not sensing lower layers that the RSP observed resulted in a bias. The combined band method showed promising results. Future work will include optimization of the filtering coefficients, using the full SEAC4RS dataset.

	1st Peak		2nd Peak		3rd Peak	
	N_p	Error [km]	N_p	Error [km]	N_p	Error [km]
1880 nm	58254	0.665695	3900	1.478279	1150	2.318882
670 nm	55241	1.050939	5902	2.033936	2314	2.801738
Combined	61918	0.770760	5457	1.570128	1787	2.444134

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References

Alexandrov, M.D., B. Cairns, C. Emde, A.S. Ackerman, and B. van Diedenhoven (2012), Accuracy assessments of cloud droplet size retrievals from polarized reflectance measurements by the research scanning polarimeter. Remote Sens. Environ., 125, 92-111

Cairns, B., L. D. Travis, and E. E. Russell (1999), The Research Scanning Polarimeter: Calibration and ground-based measurements, Proc. SPIE Int.Soc.Opt.Eng.,3754,186.

IPCC, (2013) Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, U.K. and New York, NY, USA.

Marchand, R. (2013), Trends in ISCCP, MISR, and MODIS cloud-top-height and optical-depth histograms, *J. Geophys. Res. Atmos.*, 118, 1941–1949, doi:10.1002/jgrd.50207.

van Diedenhoven, B., Fridlind, A. M., Ackerman, A. S., & Cairns, B., (2012). Evaluation of hydrometeor phase and ice properties in cloud-resolving model simulations of tropical deep convection using radiance and polarization measurements. *Journal of the Atmospheric Sciences*, *69*(11), 3290-3314.

van Diedenhoven, B., Fridlind, A. M., Cairns, B., & Ackerman, A. S. (2014). Variation of ice crystal size, shape, and asymmetry parameter in tops of tropical deep convective clouds. *Journal of Geophysical Research: Atmospheres*,*119*(20), 11-809.